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Characteristic Evaluation of a Wireless Capsule Microrobotic System

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***Abstract* –In this paper, we proposed a wireless capsule microrobotic system. The wireless capsule microrobotic system consists of a 3-axes Helmholtz coils and a wireless capsule microrobot. The wireless capsule microrobot is composed of a spiral outer shell and an o-ring type magnet. The length of wireless capsule microrobot is 20 mm and the width is 8 mm. The structure of wireless capsule microrobot is simple. The robot can suitable for multiple working environments with good stability. Total, the wireless capsule microrobot realizes multiple degrees of freedom motion by changing the current of the rotational magnetic field. Based on motion experiments, the main parameters are evaluated. The experimental results show that the wireless capsule microrobot of spiral motion has a maximum speed of 10.01 mm/s at 17 Hz in the horizontal plane and a maximum speed of 3.64 mm/s at 14 Hz in the vertical plane. The wireless capsule microrobot can turn around 90^o and achieves accelerated motion, retarded motion and stopping in the three-dimensional space.**

Index Terms* –Wireless capsule microrobot; Rotational magnetic field; 3 axes Helmholtz coils

I. INTRODUCTION

In the world, many microrobots have been developed to satisfy the requirement of industrial and medical application. In the industrial field, the microrobot can move in the pipeline, such as soil pipeline, gas pipeline and fighting pipeline in order to check or maintain the pipeline. In the medical field, the microrobot is widely used treatment of thrombus in the blood vessel and drug delivery in the human body [1] [2] [3]. Many microrobots have been developed with biomimetic locomotion, such as crawling, walking, creeping, and so on [4] [5] [6]. Guo et.al has been developed a small microrobot which like a fish in the 2002 and 2003 [7] [8]. Also, Guo et.al developed several kinds of swimming microrobot using an ICPF actuator in the 2003 [9]. The robots can turn left, right, move forward, float up and down. Behkam et al developed a remarkable biomedical swimming robot in 2005 [10]. The robot weighs 1.85 grams and is 16 mm in diameter and 46 mm in length. This robot uses a DC motor as actuator to provide propulsive force. Ian Wilding developed a high-frequency capsule robot in the 2000 [11]. Most of them use the ICPF actuator or the traditional electromagnetic motor. Because the size of robot is too small, the power is always supplied by a cable. Therefore, these microrobots are not suitable for human surgery or drug delivery.

With the development of Magnetic actuation technology, wireless microrobot which driven by Magnetic has become more and more popular. One or more magnets are placed in the microrobot. And then, the microrobot can be driven by an external magnetic field. This robot is very suitable for human surgery or drug delivery because the small size and long working time. Honda developed a new type of wireless microrobot with a tail fin which can only move in one direction in the 2001 [12]. Mei tao developed another kind of wireless microrobot driven by a new intelligent magnetic material in the 2002 [13]. Khamesee designed a microrobotic system in the 2002 [14]. Guo and Pan developed a novel type of biomimetic microrobot driven by an external magnetic field has in the 2007 and 2008, [15] [16]. It can move by a tail, which likes a fish. This fish robot can move wireless by using outside magnetic field. This robot also can change orientation by changing direction by the outside magnetic field. But the wireless microrobot can only move in the one-dimensional. Also, Guo and Pan developed a wireless microrobot which can only move in the two-dimensional space in the 2008 and 2009 [17] [18]. Chungseon Yu has been developed a drilling of intravascular microrobot, which can treat the thrombus in our blood vessel [19]. However, all of the mentioned robots are difficult to realize flexible motion by the magnetic field, and they just can move in two-dimensional space. In order to overcome these disadvantages, we use the 3 axes Helmholtz coils to generate rotational magnetic field in order to control the wireless capsule microrobot which has a magnet in its body. To realize the energy supply by wireless and flexibility movement, we propose a wireless capsule microrobotic system. The system consists of a 3 axes Helmholtz coils, a wireless capsule microrobot and usb camera. Some characteristics of magnetic field have been studied on [20] [21].

This paper is structured as follows. First, we introduce the wireless capsule microrobotic system. Second, we introduce the control principle. Third, we evaluate the characteristics of the wireless capsule microrobot and present the characteristics of the wireless capsule microrobot. The final part of the paper presents our conclusions.

II. Wireless capsule microrobotic system

The wireless capsule microrobotic system comprises two main components. One is 3 axes Helmholtz coils. We use the 3 axes Helmholtz coils to control the wireless capsule microrobot and supply the energy. Another is the wireless capsule microrobot to meet the requirement of drug delivery and surgery.

A. 3 Axes Helmholtz coils

The power for the wireless capsule microrobot comes from the 3 axes Helmholtz coils. In order to control the wireless capsule microrobot in the three-dimensional space precisely, we analyze the 3 axes Helmholtz coils.

A single-Helmholtz coil consists of two identical circular magnetic coils that are placed symmetrically one on each side of the experimental area along a common axis, and separated by distance L equal to the radius R of the coil. Electrical current flows to the same direction in each coil. The electrical current is a variable in the coil and the relationship between magnetic flux density and current is shown in equation (1).

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{R} \tag{1}$$

Where, B is the magnetic flux density, at any point on the axis of the Helmholtz coils. N is the number of turns of coil. I is the current which is flowing in the coil. R is the radius of the coil.

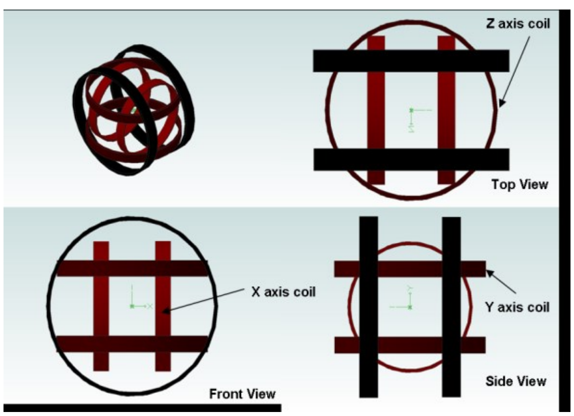


Fig. 1 The structure of the 3 axes Helmholtz coils

TABLE I

Specification of the coil system

	Turns (N)	R	L mm	Resistance (Ω)	Material
X axis coil	125	142	142	2.4	Cu
Y axis coil	150	175	175	3.3	Cu
Z axis coil	180	200	200	4.5	Cu

Combined the 3 axes Helmholtz coils, the variation magnetic field in any direction is generated. There are two methods generate the variation magnetic field. One is that we can adjust the current of the Helmholtz coil. Another is that we can rotate the Helmholtz coil. But for the second method, there is a disadvantage to the wireless capsule microrobotic system. The whole body of patient must be put into the 3 axes Helmholtz coils. In order to avoid this shortcoming, we selected the method of adjusting the current of the coil to generate the variation magnetic field. The structure and specification of 3 axes Helmholtz coils are shown in Fig. 1 and Table 1. The 3 axes Helmholtz coils can generate a uniformed magnetic field which the volume is about 0.075*0.075*0.075 meters. Therefore, the wireless capsule microrobot can realize stable motion in this area.

B. The structure of the wireless capsule microrobot

Wireless capsule microrobot is a carrier in process of drug delivery. The main requirements for the Wireless capsule microrobot are shown below:

(a) Simple structure
(b) High propulsion force
(c) Good stability
(d) Various locomotion
(e) Functional in multiple working environments
(f) Small size

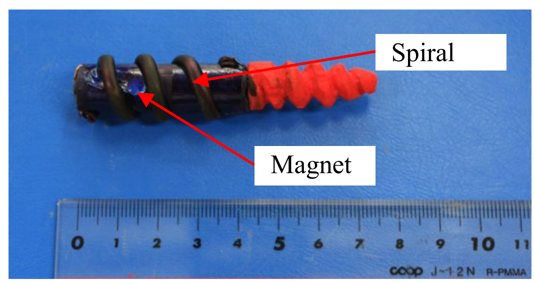


Fig. 2 Wireless microrobot of four-permanent magnet

Based on the magnetic theory, rotation of the microrobot in a magnetic field requires at least a pair of force in opposite directions, a moment should be generated. In our previous research, we proposed a wireless microrobot of four-permanent magnet as shown in Fig. 2. But the size of this robot is too big to move in the blood vessel. Also the parameters are not identical. So that the size of the wireless capsule microrobot gets complicated and it does not stability. So, in this paper, we proposed a more efficient design of the wireless capsule microrobot, as shown in Fig. 3 and the prototype is shown in Fig. 4. From the main parameters of the new microrobot in Table II, it is obvious that the new design of microrobot is smaller than the previous one.

This wireless capsule microrobot consists of two main parts, a spiral outer shell and an o-ring type magnet as actuator. The spiral outer shell is made of polythene plastic. The spiral outer shell and the o-ring type magnet are connected by a strong adhesive. So we use the o-ring type magnetic in the wireless capsule microrobot. The o-ring type shows in the Fig. 5 and the size of the o-ring magnet is shown in Table III.

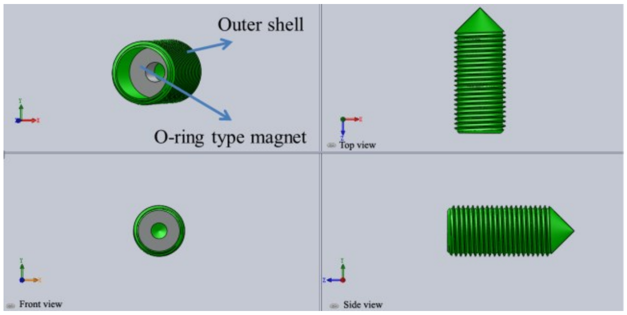


Fig. 3 The structure of the wireless capsule microrobot

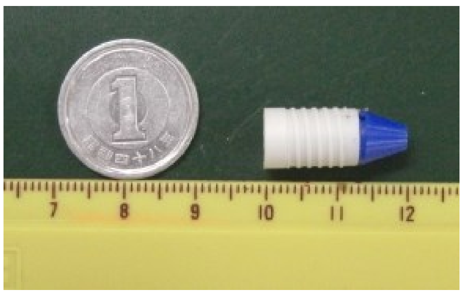


Fig. 4 Prototype of the wireless capsule microrobot

TABLE II

Parameters of the wireless capsule microrobot

Length	Radial	Weight	Material of the body
20 mm	8 mm	2.306 g	polythene plastic

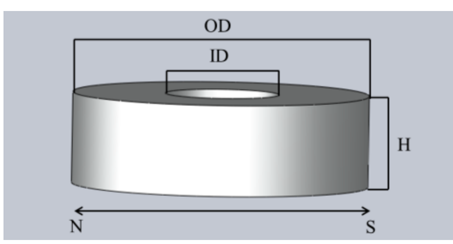


Fig. 5 The o-ring type magnet

Table III

Parameters of the o-ring type magnetic

Outer diameter	Internal diameter	Height	Magnetic field	Weight	Magnetization direction
6 mm	3 mm	4 mm	385 mT	1.036g	radial

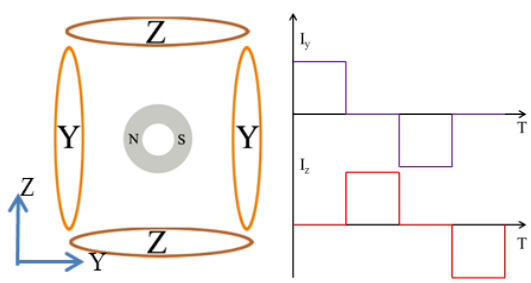
The outer shell of the wireless capsule microrobot has a spiral structure which likes a drill. The spiral structure can supply a high propulsive force while the wireless capsule microrobot is rotating by orthogonally rotating magnetic field which is generated by the 3 axes Helmholtz coils. And then, the wireless microrobot destroys obstacle and continues to move forward or turning in the pipe or blood vessel. Due to the energy of the wireless capsule microrobot is supplied by a rational magnetic field. It can work for a long-time in the human body. It is very important for medical application especially treatment of thrombosis. Also, the spiral motion mode has good stability in fluids. Because of the size of the wireless capsule microrobot is smaller than a commercial capsule endoscope. It is easier to move in the narrow space of human body.

III. Control Principle

In order to control the wireless capsule microrobot accurately, we should analyze the propulsive force of the wireless capsule microrobot. The propulsive force generates by the rotational magnetic field. We control the current of the 3 axes Helmholtz coils to provide propulsive force for the wireless capsule microrobot.

A. The rotational magnetic field.

The direction of the magnetic is always aligned along the axial directions. It can also happen that the anisotropy direction itself is not aligned with the correct axis of the magnet. Based on the magnetic theory, we used the 3 axes Helmholtz coils generate the orthogonally rotating magnetic field. The Fig. 6 shows that the orthogonally rotating magnetic is generated in the Y-Z plane when the current is flowing in the Helmholtz coil pairs. The Helmholtz coil Y generates the magnetic field in the Y axes and the Helmholtz coil Z generates the magnetic field in the Z axes. Fig. 6 (b) shows the current of the Helmholtz coil pairs, the directions of current with a 90° phase difference. Through changing the frequency of input current, the rotational speed of magnet in the microrobot is changed. The magnet is fixed on the micro robot. So the microrobot is driven by the 3 axes Helmholtz coils. The forward and backward motion can be realized by changing the direction of current. By changing the value of the current, the direction of the wireless capsule microrobot can be turned in the three dimensional space.



(a) Y-Z Helmholtz coil (b) the current of the coil

Fig. 6 Principle of the orthogonally rotating magnetic

B. The calculation of propulsive force and torque

The propulsive force and torque is provided by rotating the wireless capsule microrobot. When the wireless capsule microrobot is rotated, it can generate a propulsive force. Therefore, the wireless capsule microrobot can realize 3D motion. In order to overcome fluid resistance in the pipe, we can change magnetic force and torque with the Helmholtz coil pairs, the equations (2) and (3) as follows:

$$T = \mu_0 V M \times H \times \sin\theta \tag{2}$$

$$F = \mu_0 V (M \bullet \nabla) H \times \sin\theta \tag{3}$$

where, M is the average magnetization, V represents the volume of the body. ∇ represents a gradient operator. θ is the angle of between M and B.

Wireless capsule microrobot along the axis of a propulsive force is described by a symmetric propulsion matrix as shown equations (4) relating the four principle scalar, as shown the Fig. 7 [22].

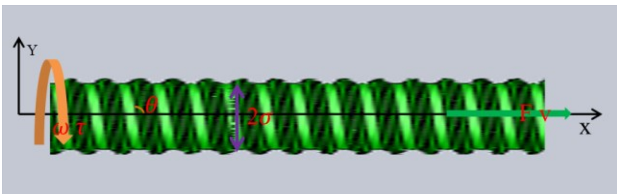


Fig. 7 Spiral model of the wireless capsule microrobot

$$\begin{pmatrix} f \\ \tau \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} v \\ \omega \end{pmatrix} \tag{4}$$

where, f is non-fluidic applied force, $\tau$is the non-fluidic applied torque, υ is forward velocity and ω is angular speed. The matrix parameters are computed as equations (5-8)

$$a_{11} = 6.2n\sigma\left(\frac{k_1\cos^2\theta + k_2\sin^2\theta}{\sin\theta}\right) \tag{5}$$

$$a_{12} = 6.2n\sigma\left(k_1 - k_2\right)\cos\theta \tag{6}$$

$$a_{12} = a_{21} \tag{7}$$

$$a_{22} = 6.2n\sigma\left(\frac{k_2\cos^2\theta + k_1\sin^2\theta}{\sin\theta}\right) \tag{8}$$

Where, the k_1 and k_2 are the constants, which are the viscous drag coefficients for the wireless capsule microrobot along the axis. σ and θ are shown in the Fig. 7.

IV. Experiments and Results

In order to evaluate the characteristic of the wireless capsule microrobot, we designed the experimental setup. Fig. 8 is shown the experimental setup including drive circuit, DC supply, the 3 axes Helmholtz coils and PC. The 3 axes Helmholtz coils can generate a rotation magnetic field, which control the wireless capsule microrobot to move in the pipe. We use PC to generate the drive signals of the 3 axes Helmholtz coils. And we use a camera to record the motion of the wireless capsule microrobot.

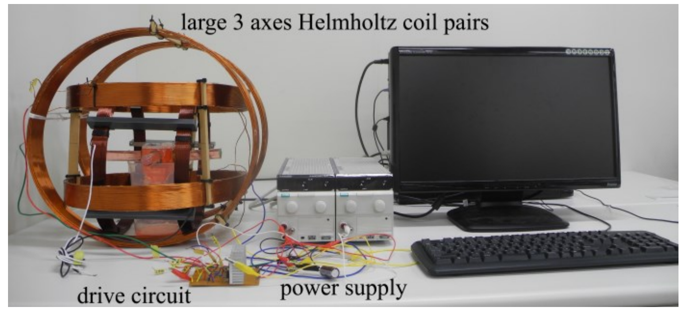
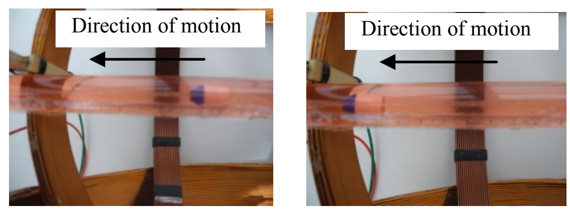


Fig. 8 Experimental setup

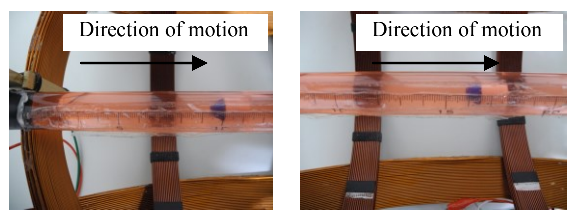
A. *Rectilinear motion*

The rectilinear motion is normal but high frequency when the microrobot is working in the blood vessels. So it is important to achieve the good rectilinear motion. In order to evaluate the characteristics of the wireless capsule microrobot, four experiments are carried out in the water pipe. Water density is 998.203 kg/m^3 and the temperature is 22^{o}C. Fig. 9 shows it move forward in horizontal plane. By adjusting the direction of the input current, the wireless capsule microrobot can move backward, as shown in Fig. 10.



(a) t=0 s (b) t=5s

Fig. 9 Forward motion in horizontal plane



(a) t=0 s (b) t=5s

Fig. 10 Backward motion in horizontal plane

Fig. 11 shows the relationship between the rotational frequency and the moving speed of wireless capsule microrobot in the horizontal plane. The largest moving speed is 10.01mm/s at the frequency of 17 Hz.

Fig. 12 shows the wireless capsule move in the vertical plane in the water pipe by the rotational magnetic field. The relationship between the rotational frequency and the moving speed of the wireless capsule microrobot in the vertical plane is shown in Fig. 13. The largest moving speed is 3.64 mm/s at the frequency of 14 Hz. The results of the experiments show that the microrobot is faster in the horizontal plane (Fig. 11) than it is in vertical the plane (Fig. 13) at 14 Hz. Because the propulsive force (f) overcomes gravity (f_g) in the vertical plane, the equations (9) and (10) as follows:

In the horizontal plane:

$$f=a_{11}v+a_{12}\omega \tag{9}$$

In the vertical plane:

$$f-f_g=a_{11}v+a_{12}\omega \tag{10}$$

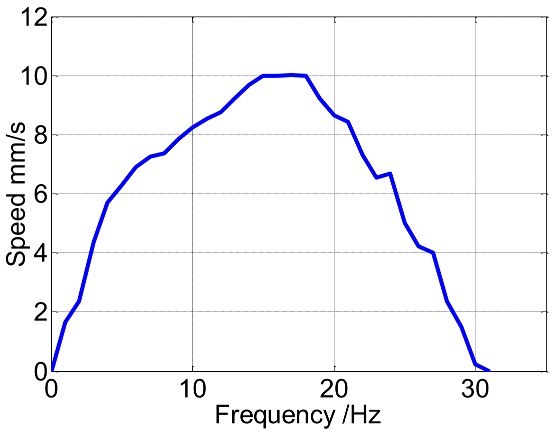
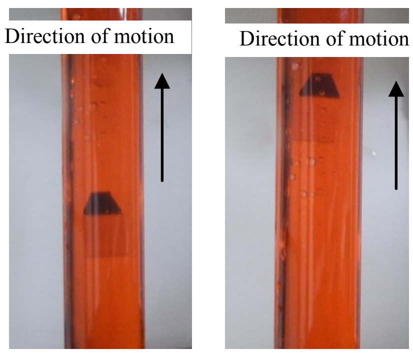


Fig. 11 Relationship between frequency and speed in the horizontal plane



(a) t=0 s (b) t=5s

Fig. 12 Forward motion in the vertical plane

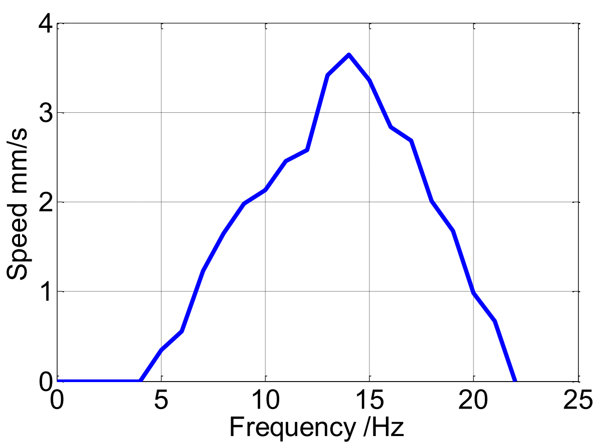
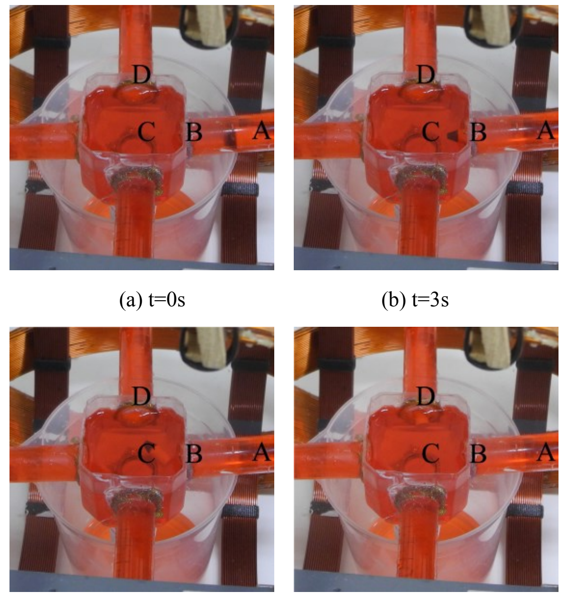


Fig. 13 Relationship between frequency and speed in the horizontal plane

B. Turning motion

Fig. 14 shows the wireless capsule microrobot turned in the X-Y horizontal plane. The process as follows:

1) The wireless capsule microrobot moves along the X axis from point A to point B.
2) By adjusting the frequency of the input current, the wireless microrobot decelerated from point B to point C.
3) At point C, the wireless capsule microrobot turns 90°. In order to rotate the rotational magnetic field by 90°, the current I_x sets as 0 and the current of coil y sets I_y and the current of I_z remains unchanged. The wireless capsule microrobot turns around from point C to point D.
4) The wireless capsule microrobot accelerated.



(a) t=0s (b) t=3s

(c) t=6s (d) t=9s

Fig. 14 The microrobot turned in the X-Y horizontal plane

C. Variable speed motion

The wireless capsule microrobot realized variable speed motion in horizontal plane. The relationship between rotational frequency and the moving speed of the wireless capsule microrobot as shown in the Fig. 15. The process as follows:

1) The microrobot moves in the in horizontal direction at 1 Hz.
2) By adjusting the frequency of the input current, it moves at 5 Hz and 15 Hz.
3) We adjust the frequency to 0 Hz. The wireless capsule microrobot stops at a point in the pipe.
4) By adjusting the frequency of the input current, the wireless capsule microrobot moves at 15 Hz and 5 Hz, and it stops in the pipe at the 0 Hz.

The results of the experiments show that the wireless capsule microrobot can moved in the low-frequency, through changing the direction of current which is flowing through Helmholtz coil pairs, the wireless capsule microrobot can moved forward and backward. By adjusting the value of the current, the direction of the wireless capsule microrobot can turned. By adjusting the frequency of the current, the wireless capsule microrobot achieves accelerated motion, retarded motion and stopping in pipe.

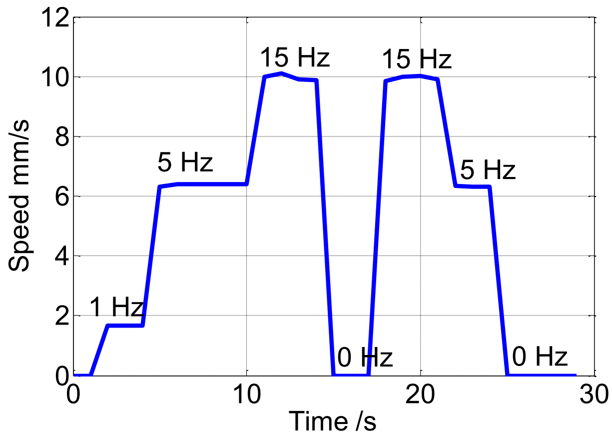


Fig. 15 The relationship between rotational frequency and moving speed

V. CONCLUSIONS

In this paper, we developed a wireless capsule microrobotic system. The system consists of a 3 axes Helmholtz coils and a wireless capsule microrobot. The 3 axes Helmholtz coils controls the wireless capsule microrobot to realize 3D motion in a pipe. We also discussed the structure of the wireless capsule of the microrobot. In order to evaluate the performance of the wireless capsule microrobotic system, we designed 5 experiments, forward motion, backward motion, upward motion, turning motion and variable speed motion.

The experiments of forward motion, backward motion and upward motion show the wireless capsule microrobot realized the rectilinear motion in the horizontal plane and in the vertical plane. In the horizontal plane, the maximum speed is 10.01mm/s. In the vertical plane, the maximum speed is 3.64 mm/s. The experiment of turning motion realized turn in the horizontal plane. In order to evaluate the flexibility in horizontal plane, the variable speed experiment is carried out. The experimental results show a good performance on flexibility.

In the future, we want to use the magnetic sensor to realize positioning of the wireless capsule microrobot in the human body.

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